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CR-174824

ALTITUDE TESTING OF THE 2D V/STOL ADEN DEMONSTRATOR ON AN F404 ENGINE

P-110

Final Report

by

J.T. Blozy

GENERAL ELECTRIC COMPANY

Prepared For

National Aeronautics and Space Administration

(NASA-CR-174824) ALTITUDE TESTING OF THE 2D V/STOL ADEN DEMONSTRATOR ON AN F404 ENGINE Final Report (GE) 110 p CSCL 21E

N90-17638

Unclas

G3/07 0270217

NASA Lewis Research Center
NAS3-23042

National Aeronautics and
Space Administration

FOREWORD

This report was prepared by the General Electric Company, Evendale Plant, under Contract NAS3-23042. The contract was administered by the National Aeronautics and Space Administration, Lewis Research Center, Cleveland, Ohio. The NASA Project Manager for the contract was Mr. R.E. Grey. Altitude testing in the Lewis Propulsion System Laboratory Facility was directed by Messrs. R.A. Lottig and L. Bryant, NASA Project Engineers. NAVAIR provided the test engines and hardware under the management of Mr. J.L. Palcza of the Naval Air Propulsion Test Center, Trenton, New Jersey.

The major contributions of Don Speir, Bill Wooten, Glen Allan, Gill Todd, and Chuck Spuckler to technical efforts described in this report are gratefully acknowledged by the author.

SUMMARY

A full-scale, flight-weight, two-dimensional Augmented Deflector Exhaust Nozzle (ADEN) was mounted on an F404 engine and tested in the NASA Lewis Propulsion System Laboratory Altitude Test Facility. Testing included 56 hours of engine running time. Of the 56 hours, over 14 were under reheat power conditions, and 6.5 hours of vector operation were accomplished. No vibration, cooling, or actuation problems were encountered during the test. Visual inspection of the ADEN following the test revealed no hardware distress resulting from the testing. Nozzle reheat temperatures up to 1937 K (3488° R) were tested along with nozzle pressure ratios up to 18. The inlet pressure was varied from 24.1 to 124.1 kPa (3.5 to 18 psi). A nominal inlet temperature of 285 K (520° R) was maintained for all test conditions. The nozzle maximum pressure loading was 331 kPa (48 psi). Vectoring using the Variable External Expansion Ramp (VEER) was demonstrated for VEER angles from -15° to +15° relative to the nominal unvectored VEER position. Nozzle performance was measured including resultant thrust coefficient, nozzle discharge coefficient, thrust vector angle, and thrust vector location. Comparisons with 1/8-scale-model data are presented.

TABLE OF CONTENTS

TABLE OF CONTENTS (Concluded)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Concluded)

NOMENCLATURE

A	Area, cm^2 (in^2)
A_8, A8	Nozzle Throat Area
A/B	Afterburner, Afterburning (Augmented, or Reheat) Power
ADEN	Augmented Deflector Exhaust Nozzle
A_e	Exit Area
ALCE	Total Effective Leakage Flow Area
CD	Convergent/Divergent
CD_8, CD8	Nozzle (Exit) Discharge Coefficient
CFGR	Resultant Thrust Coefficient, F_R/F_I
CRT	Cathode Ray Tube
D	Distance Between Forward and Aft Horizontal Load Cells, cm (in)
DELJ	Thrust Vector Angle (also δj)
EQVAB	A/B Equivalence Ratio: $WFAB/WFAB_{stoichiometric}$
F	Force (Thrust), N (lbf)
FAH	Aft Horizontal Load Cell Measured Force
FFH	Forward Horizontal Load Cell Measured Force
F_g	Gross Thrust
F_I	Ideal Thrust
FM	Frequency Modulation
F_n	Net Thrust
F_R	Resultant Thrust
F_x	Axial Thrust
F_y	Lateral Thrust
g	Gravitational Constant

GE	General Electric Company
H_{E1}	Equilibrium Total Enthalpy
H_{E2}	Equilibrium Static Enthalpy at Nozzle Throat
H_{F2}	Frozen Static Enthalpy at the Throat
H_{F3}	Frozen Static Enthalpy at Ambient Pressure
J	Joule Constant
L	Length, cm (in.)
LPT	Low Pressure Turbine
LVDT	Linear-Variable Differential Transformer
$(mv)_e$	Exit Momentum
NASA	National Aeronautics and Space Administration
NPR	Nozzle Pressure Ratio
P	Pressure, Pa (psi)
P_2	Inlet Pressure
P_8	Nozzle Throat Total Pressure
P_{amb}	Ambient (or Test Cell) Pressure
P_{cav}	Cavity Pressure
P_e	Exit Pressure
P_S	Static Pressure
PSL	Propulsion System Laboratory
P_T	Total Pressure
R	Gas Constant
RN	Reynolds Number, $\rho VL/\mu$
SERN	Single Expansion Ramp Nozzle

NOMENCLATURE (Concluded)

SLS	Sea Level Static
T	Temperature, K (° R or ° F)
T_8	Gas Temperature at Nozzle Throat
T_T	Total Temperature
V	Flow Velocity, m/s (ft/s)
VEER	Variable External Expansion Ramp
V/STOL	Vertical/Short Takeoff and Landing
VTOL	Vertical Takeoff and Landing
W	Mass Flow Rate, kg/s (lbm/s)
W_8	Gas Flow at Nozzle Throat
W_{8_I}	Ideal Mass Flow Rate
WFAB	A/B Fuel Flow
WFM	Main (Combustor) Fuel Flow
XN	Thrust Vector Location
XNH	Core Speed
XNL	Fan Speed
2D	Two Dimensional
γ	Ratio of Gas Specific Heat at Constant Pressure to Specific Heat at Constant Volume
γ_8	Specific Heat Ratio at Nozzle Throat
δ_j	Thrust Vector Angle (also DELJ)
ΔP	Pressure Drop or Differential
μ	Coefficient of Absolute Viscosity
ρ	Fluid Density

1.0 BACKGROUND AND INTRODUCTION

This report summarizes the evaluation of a flight-weight, self-cooled, engine-controlled, two-dimensional (2D), thrust-vectoring exhaust system. The Augmented Deflector Exhaust Nozzle (ADEN) was successfully tested behind a General Electric F404 turbofan engine in the NASA Lewis Propulsion Laboratory Altitude Test Facility. This evaluation provides the first data on any 2D nozzle over such a wide range of operating conditions.

The ADEN was identified under the Navy Advanced Vertical/Short Takeoff and Landing (V/STOL) Propulsion-Component Development Program as being the thrust-vectoring concept with the highest aircraft/engine system payoff for multimission V/STOL fighter applications (Reference 1). As shown in Figures 1 and 2, the ADEN is a 2D, variable-area, thrust-vectoring, Single Expansion Ramp Nozzle (SERN). Basic ADEN components consist of: (1) a transition casing from a round cross section at the tailpipe connecting flange to a 2D (rectangular) cross section at the nozzle throat station; (2) a 2D, variable-geometry, convergent/divergent (CD) flap assembly; (3) a 2D, variable-position, ventral flap; (4) a 2D, external-expansion ramp that can be fixed or variable depending on specific installation requirements; and (5) a rotating deflector for thrust vectoring. As illustrated in Figure 3, the ADEN design varies A_8 by means of a moveable flap arrangement on the upper surface. The expansion ratio is changed by the rotatable ventral flap. In-flight thrust vectoring of up to 30° deflection is provided by the Variable External Expansion Ramp (VEER). The rotating deflector "bonnet" enables continuous thrust vectoring for V/STOL operation. In the stowed (cruise mode) position, the deflector is located outside the nozzle casing so that it does not compromise the required internal flowpath contours. The bonnet was locked up and not used for this test program. An internal cooling system (Figure 4) utilizes available engine (fan) flow to maintain nozzle surface temperatures at or below design levels (Reference 2).

Under the Navy program, the General Electric Aircraft Engine Business Group in Evendale, Ohio designed, fabricated, assembled, and tested a flight-type ADEN on a YJ101 engine as a demonstration. The full-scale ADEN demonstrator was first tested on a YJ101 engine at sea level, static conditions at the General Electric Peebles Test Operation, Peebles, Ohio (Figure 5). Over 40 hours of nozzle test time were accumulated at various power settings and nozzle thrust-deflection modes. The major part of the deflected testing was for VTOL; exhaust gas temperature (T_8) ranged from dry power (about 833 K or 1500° R) to afterburning (A/B, about 1967 K or 3540° R).

Results from the Peebles test were quite favorable. Thrust coefficients were within the estimated performance band and verified scale-model test results that showed the ADEN provides high performance in both forward- and vectored-thrust modes. Maximum augmentation (A/B) temperatures were run with no significant problems. The objective T_8 of 1833 K (3300° R) for VTOL operation was exceeded by over 111 K (200° R). The actuation system worked as designed, and loads were less than expected. The cooling system maintained the average nozzle metal temperatures at or below the design levels.

Figure 1. ADEN Mounted on the YJ101 Engine.

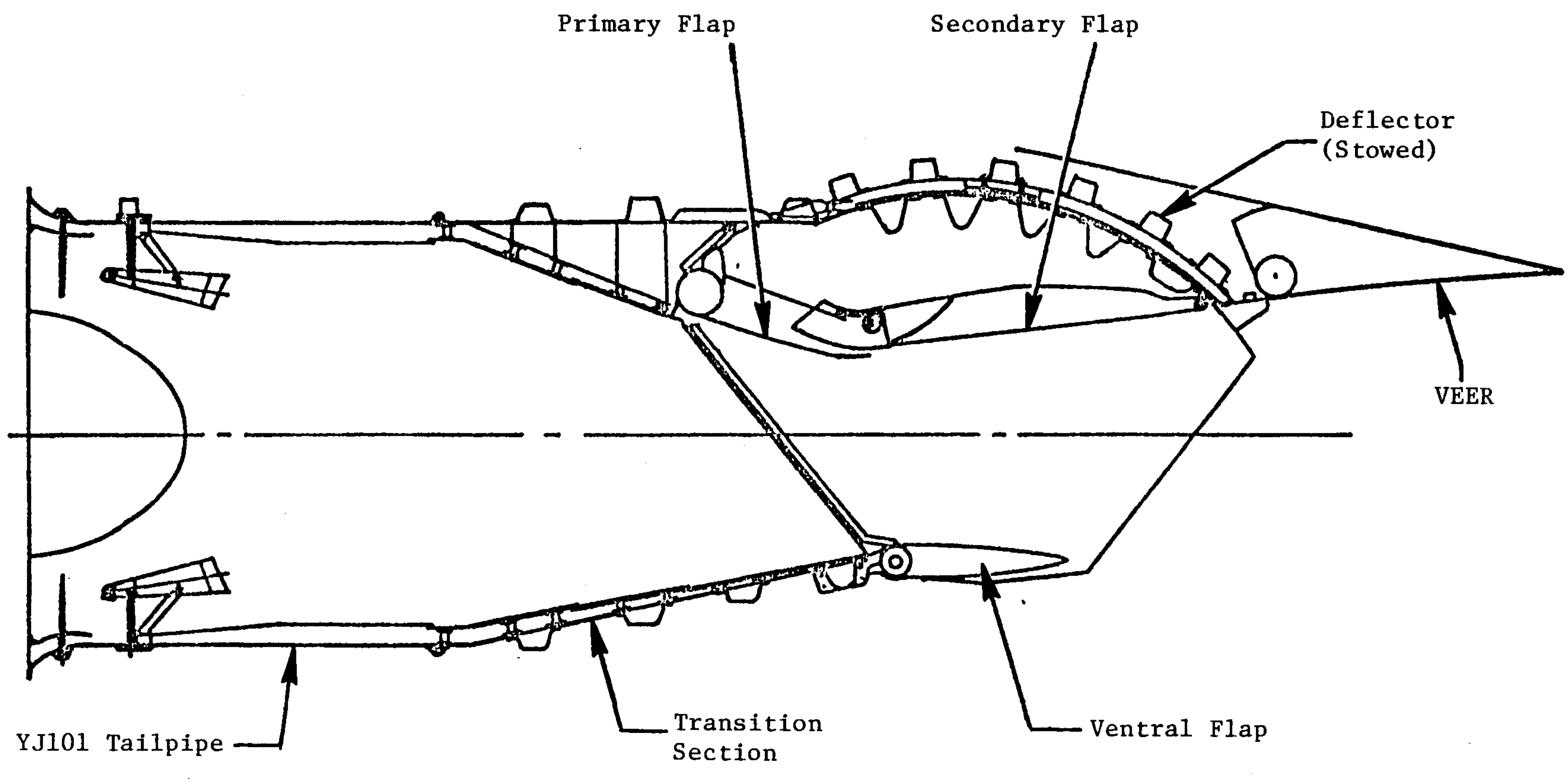
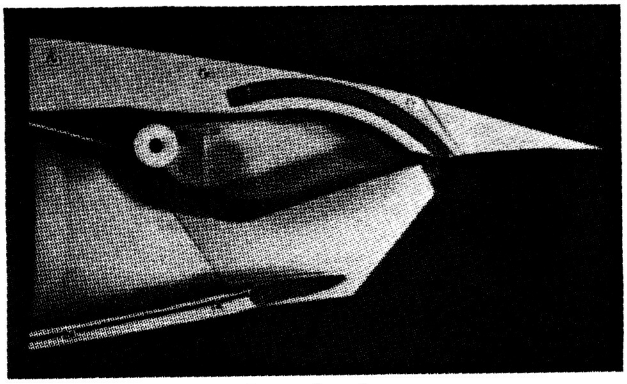
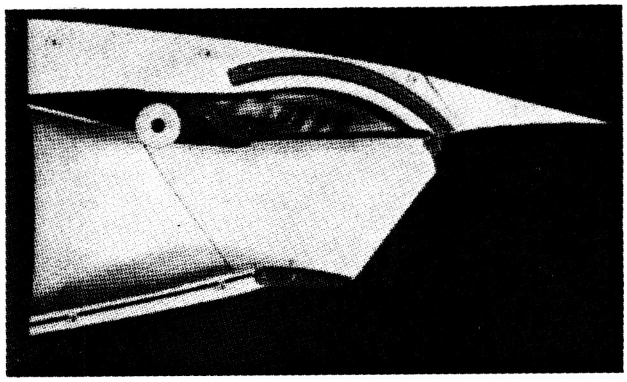


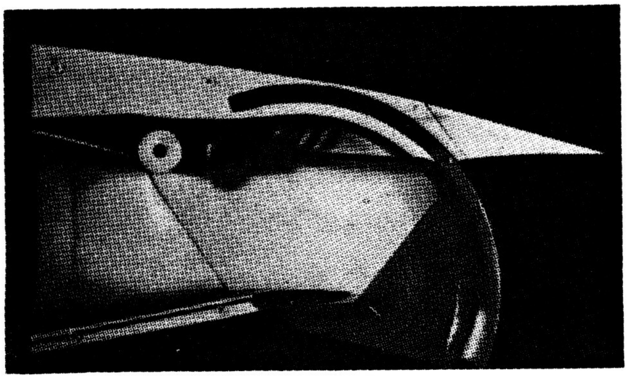
Figure 2. ADEN Flowpath and Components.



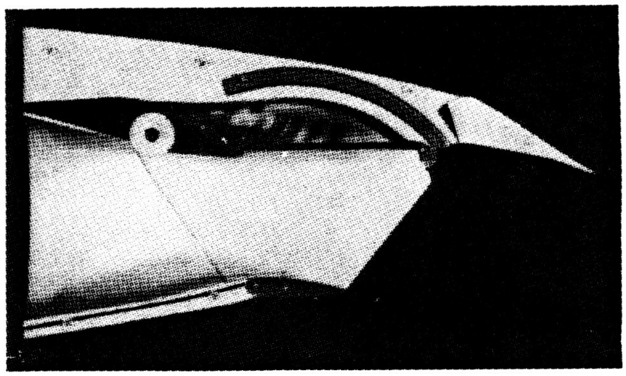
Dry Cruise



Max A/B



VTOL



In-Flight Vectoring

Figure 3. ADEN Throat Area and Vector Angle Control.

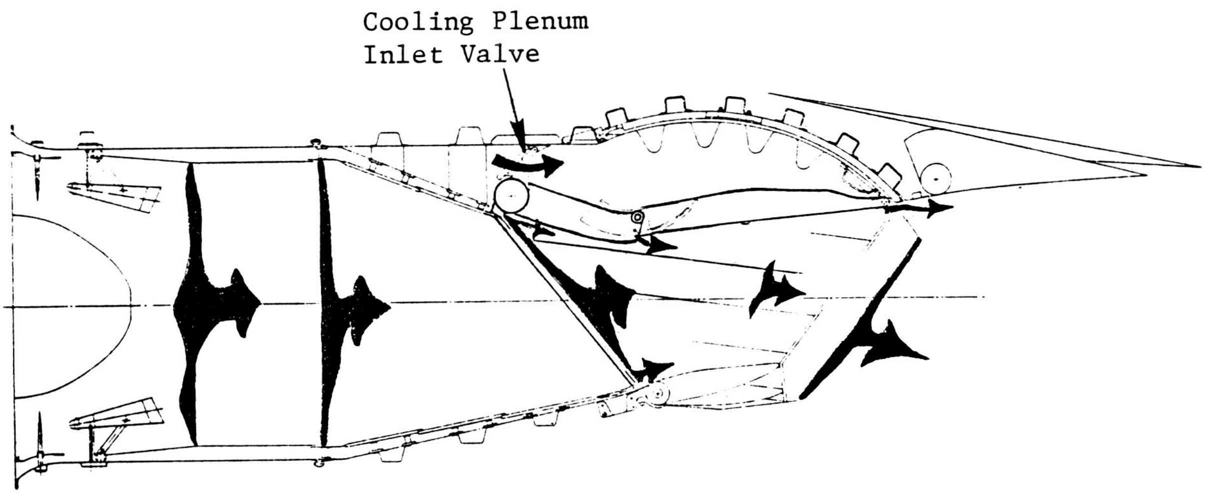


Figure 4. ADEN and Augmentor Cooling-Flow (Fan Air) Distribution.

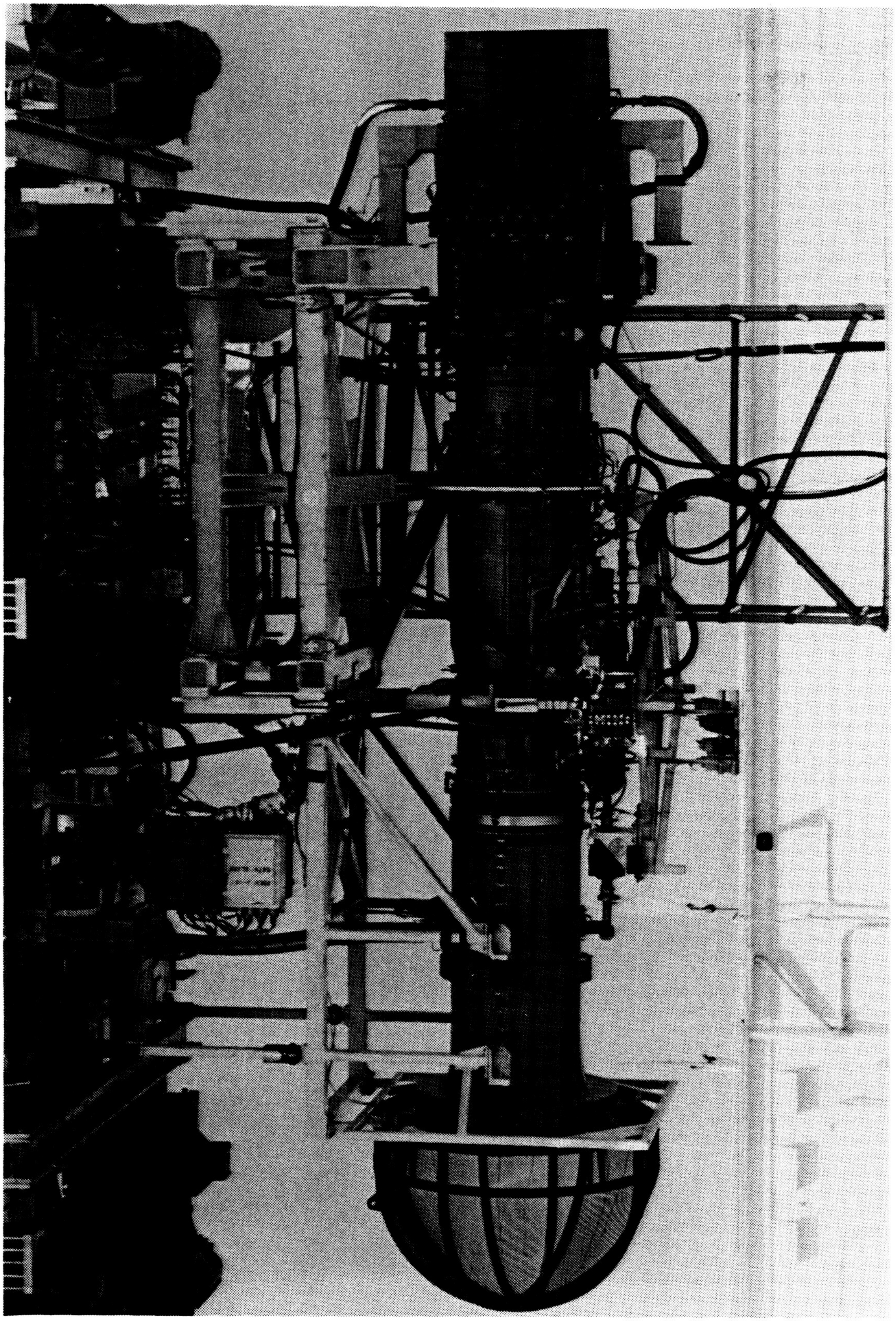


Figure 5. ADEN/YJ101 on the Test Stand at Peebles.

Following the YJ101/ADEN test at Peebles, the same engine and nozzle were tested by the Navy at the Lakehurst test facility to evaluate infrared radiation (IR) signature characteristics of the ADEN. This test involved another 40 hours of dry-power testing at sea level, static conditions, bringing the total engine running time for the ADEN to over 80 hours.

The YJ101/ADEN testing, although highly successful, was limited to ground level, static testing. As the next step in development of nonaxisymmetric, thrust-vectoring exhaust systems, the NASA Lewis Research Center, at the request of the Navy, conducted an altitude test. The objective of the NASA program was to evaluate aerodynamic performance, cooling-system effectiveness, and mechanical operation of the ADEN over a range of Mach number and altitude operating conditions. The test was conducted using the existing ADEN mounted behind an F404 engine, which is slightly larger than the YJ101 engine. Testing included nozzle pressure ratios up to 18, design pressure loading on the exhaust system [exhaust total pressure minus ambient pressure, ΔP = 331 kPa (48 psi)], and dry and A/B power for both unvectored and vectored operation. Vectoring was accomplished using the VEER, with VEER angle settings ranging from -15° to +15°.

This altitude test and the resulting data are the subject of this report. Portions of the data were reported in Reference 3.

2.0 APPARATUS

This section describes the test hardware and the NASA Lewis Propulsion Laboratory Altitude Testing Facility.

2.1 TEST HARDWARE

The test hardware consisted of the ADEN, the F404 engine, and the conical nozzle. Modifications to the F404 augmentor were necessary to accommodate the ADEN and the conical nozzle. The measuring system for VEER cooling flow is also described. Control systems developed for the test program are discussed, instrumentation is defined, and details of the F404/ADEN installation at the NASA Lewis test facility are presented.

2.1.1 ADEN

Details of the ADEN flowpath, actuator system, and cooling system are described in the following subsections.

2.1.1.1 Flowpath

The ADEN, shown in Figure 6, is a two-dimensional, variable-area, external-expansion exhaust system. Photographs of the ADEN are shown in Figures 7 and 8. Basic components consist of:

A. Transition Casing - The ADEN transition casing provides a smooth change in shape from a round cross section at the forward engine mounting flange to a two-dimensional cross section at the nozzle throat station. The change in shape was designed to take place in the shortest possible distance while minimizing the area changes and limiting all local expansion angles to 15° or less.

B. Flap Assembly - The ADEN throat area is regulated by actuation of a two-dimensional, variable-geometry, convergent/divergent primary/secondary flap assembly. This arrangement permits nozzle throat areas from 1200 cm^2 (186 in^2) to 2626 cm^2 (407 in^2) to be set. The flaps are designed to provide efficient thrust recovery for a wide range of area settings and nozzle pressure ratios. This throat-area variation is illustrated in Figure 9, which shows the ADEN flowpath.

C. Variable Ventral Flap - A two-dimensional, variable, ventral flap, located downstream of the nozzle throat, controls the nozzle expansion area ratio as required over the range of operating pressure ratios.

D. VEER - A two-dimensional, external expansion ramp, which can be fixed or variable depending on specific installation requirements, provides the capability of thrust vector control. Rotation of the expansion ramp will provide an upward or downward vertical thrust component as desired.

E. Rotating Deflector - In the V/STOL (deflected mode) position, the rotating deflector diverts the jet downward, providing continuous thrust vectoring from the forward-mode operation to VTOL, or beyond. The nozzle flap assembly is rotated to the maximum-open position to abate the Mach number of the flow approaching the turn. The throat is established between the tip of the ventral flap and the deflector. In the stowed (forward mode) position, the deflector is outside the casing so that it does not compromise the required internal flowpath contours. For this program, the rotating deflector always remained in the stowed position.

2.1.1.2 Actuator System

Simplicity and reliability have been emphasized throughout the ADEN actuation system design. The motion of the three nozzle flaps is scheduled by cam-and-link mechanisms operated by a single nozzle-area-control system. The deflector, used during V/STOL only, requires a second control system.

Nozzle area control in the cruise mode is provided by varying the convergent and divergent (upper) flaps by means of two hydraulic actuators which are casing mounted.

The ventral flap, positioned by a dual-cam mechanism, has two functions:

- Expansion area control in the cruise mode
- Nozzle throat area control in the V/STOL mode

The ventral flap must be varied during cruise-mode operation to provide efficient expansion of the nozzle flow. This variation is accomplished by a single-cam drive mechanism.

In-flight thrust vector control is furnished by a movable external expansion flap. This flap may be integrated with either the aircraft control or the engine control.

2.1.1.3 Cooling System

The ADEN cooling system provides effective, reliable cooling of exhaust system parts with the flow available from the fan stream. The coolant is ducted around the augmentor liner, distributed through structural ribs, and metered to vary cooling flow as required during cruise and vectored-mode operation. Figure 4 shows a schematic of this ADEN cooling system.

During vectored operation, the nozzle throat is rotated with the deflector so that the gas flow is turned upstream of the throat at velocities

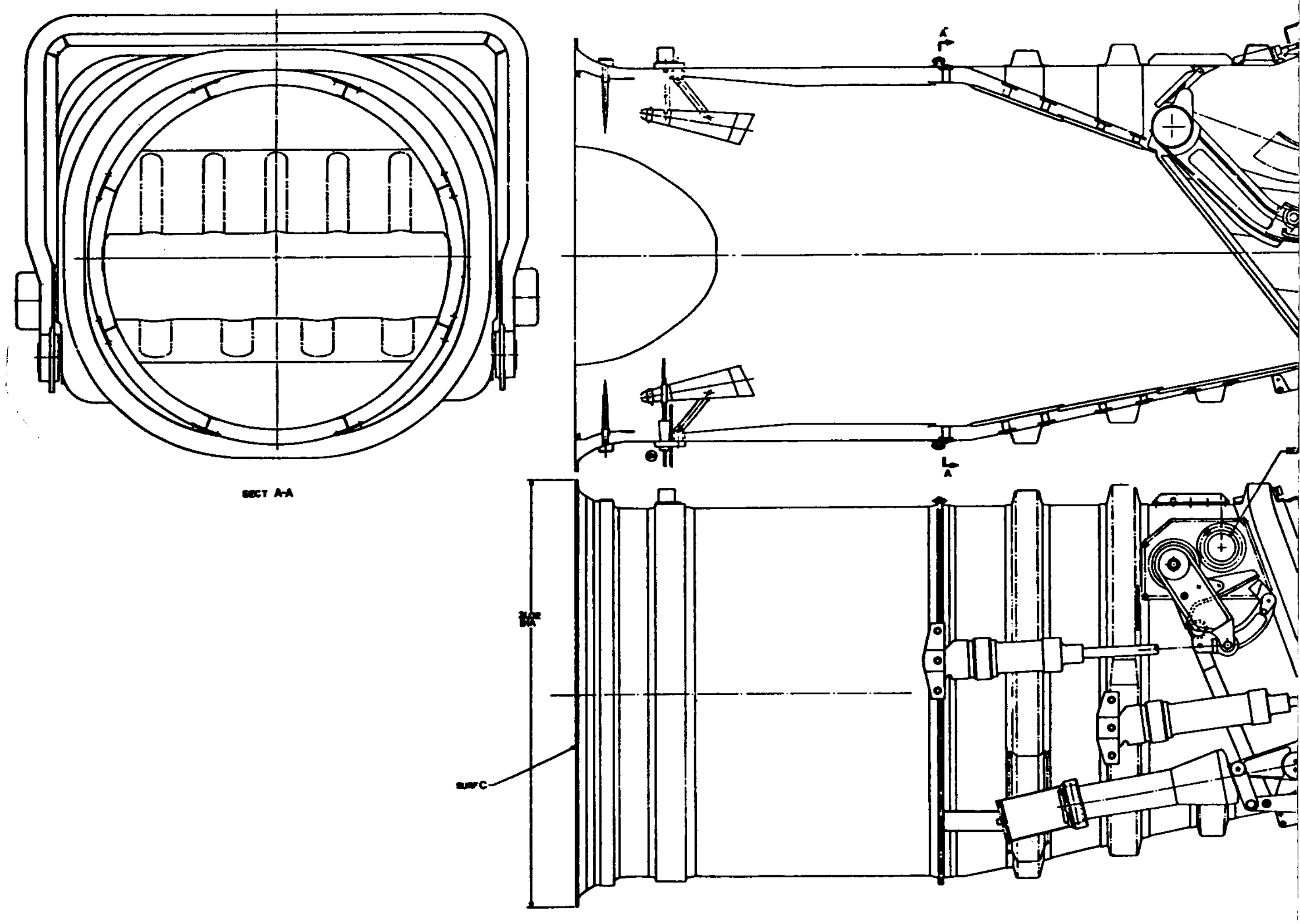
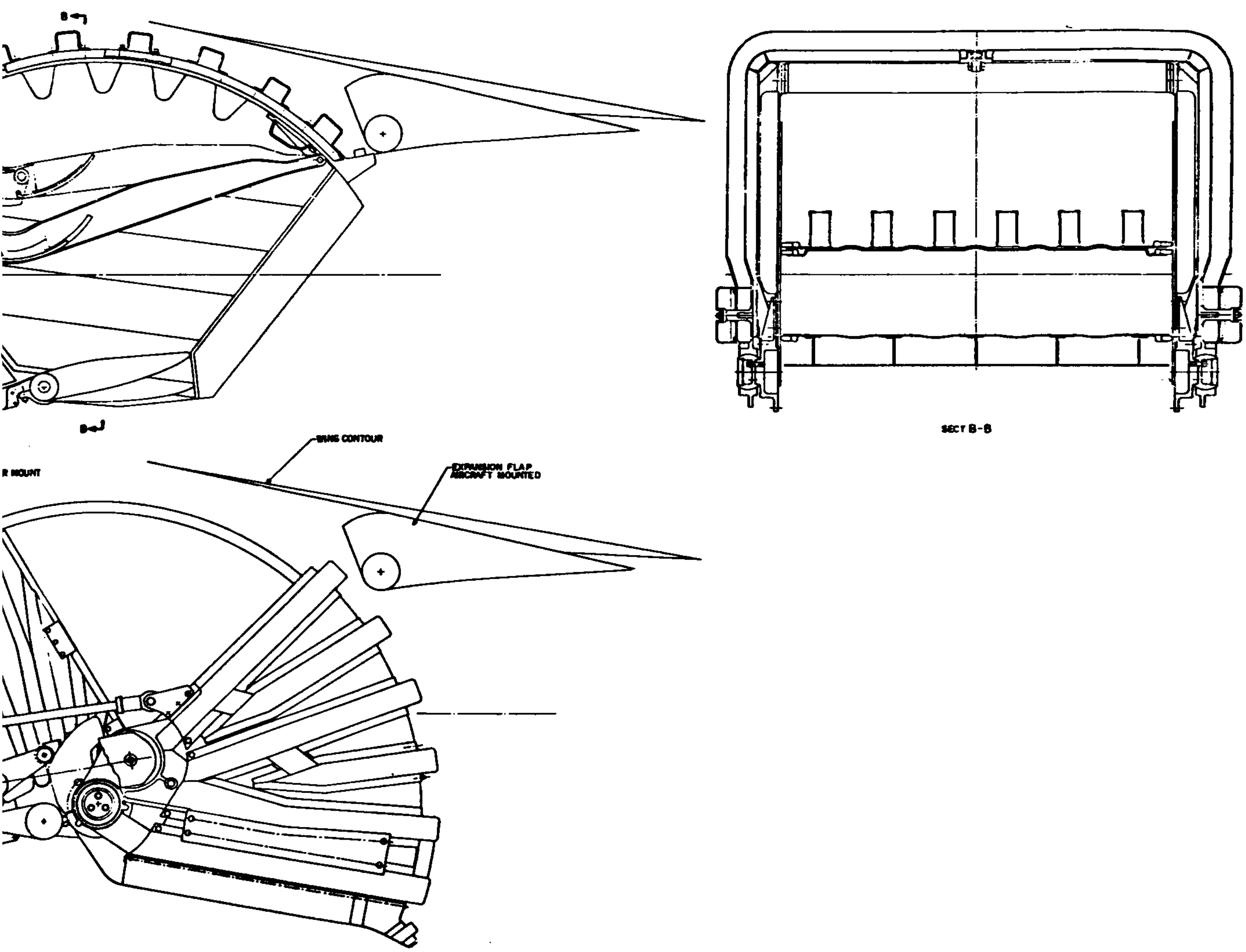


Figure 6. ADEN A



ssembly Drawing.

2 FOLDOUT FRAME

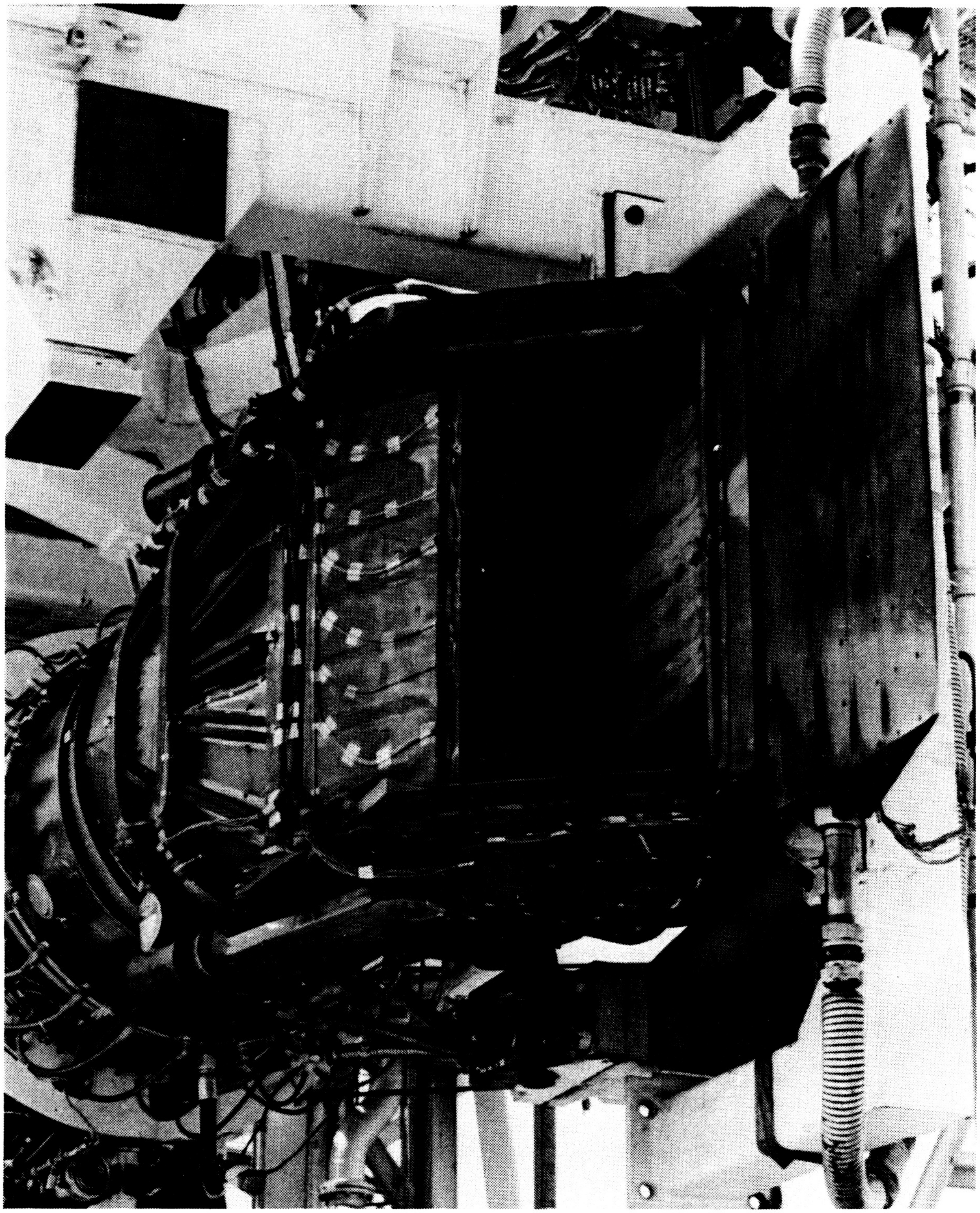


Figure 8. ADEN Demonstrator, Aft View.

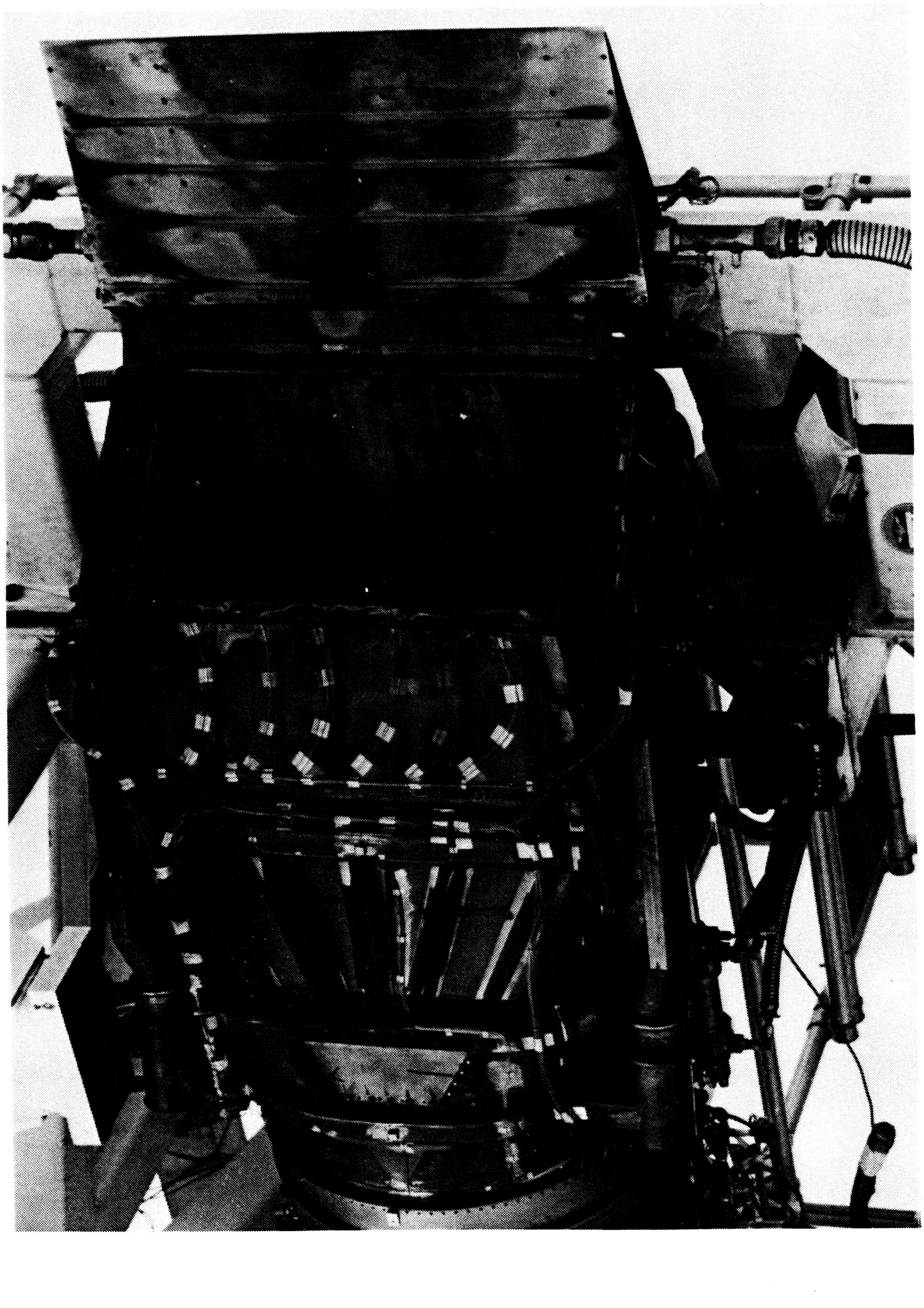


Figure 7. ADEN Demonstrator, Bottom View.

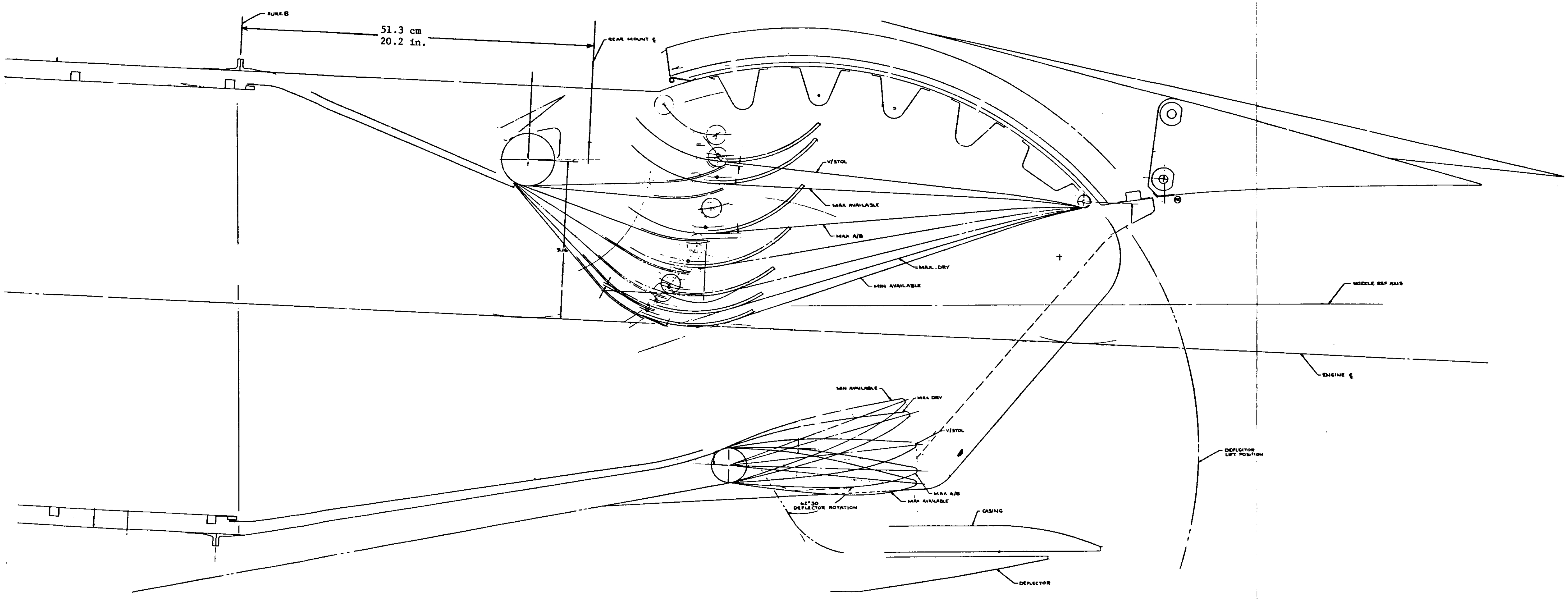


Figure 9. ADEN Demonstrator Throat Area Variation.

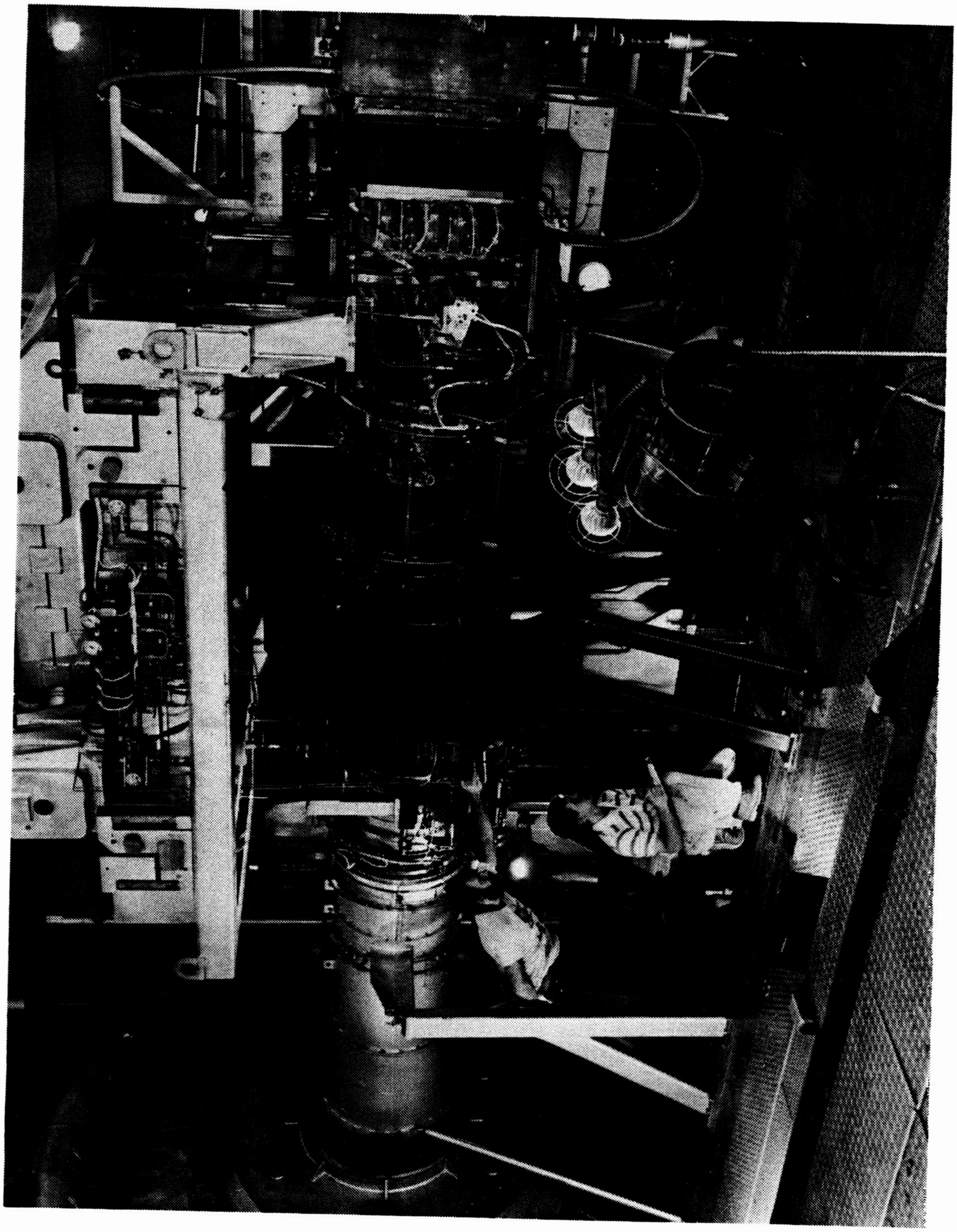


Figure 18. F404/ADEN Installation, Aft Looking Forward.

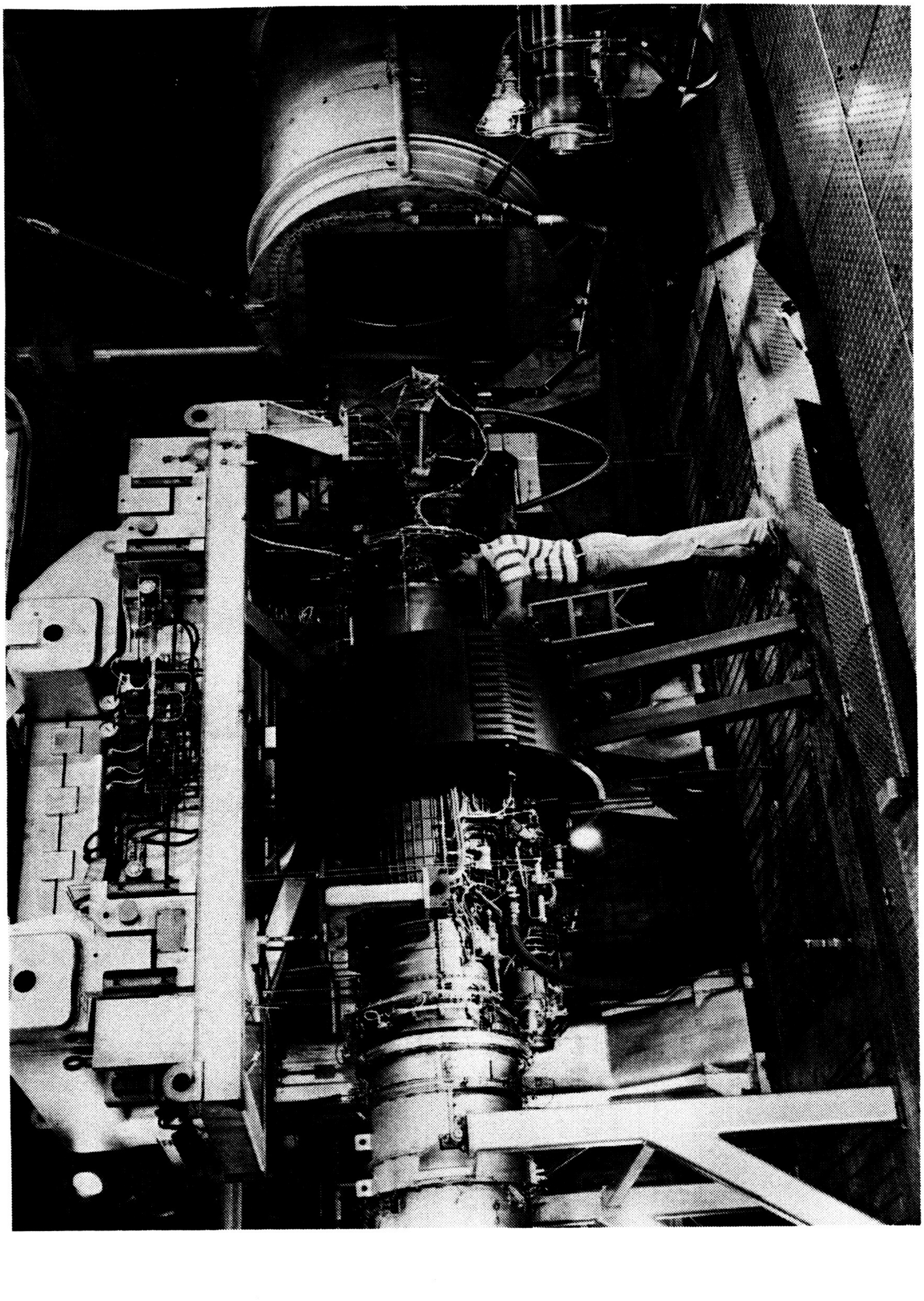


Figure 19. F404/ADEN Installation, Forward Looking Aft.

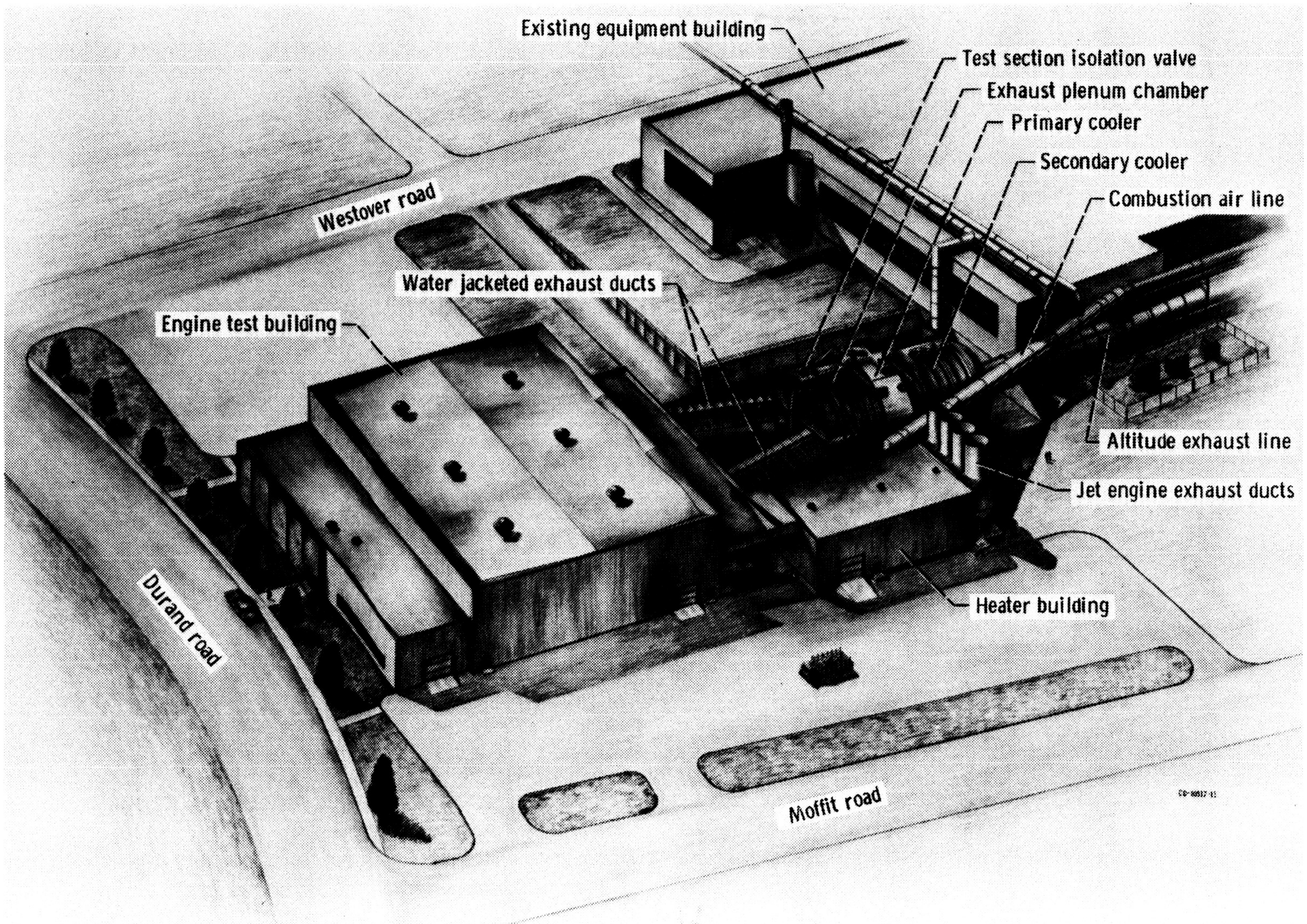


Figure 21. PSL Facility.

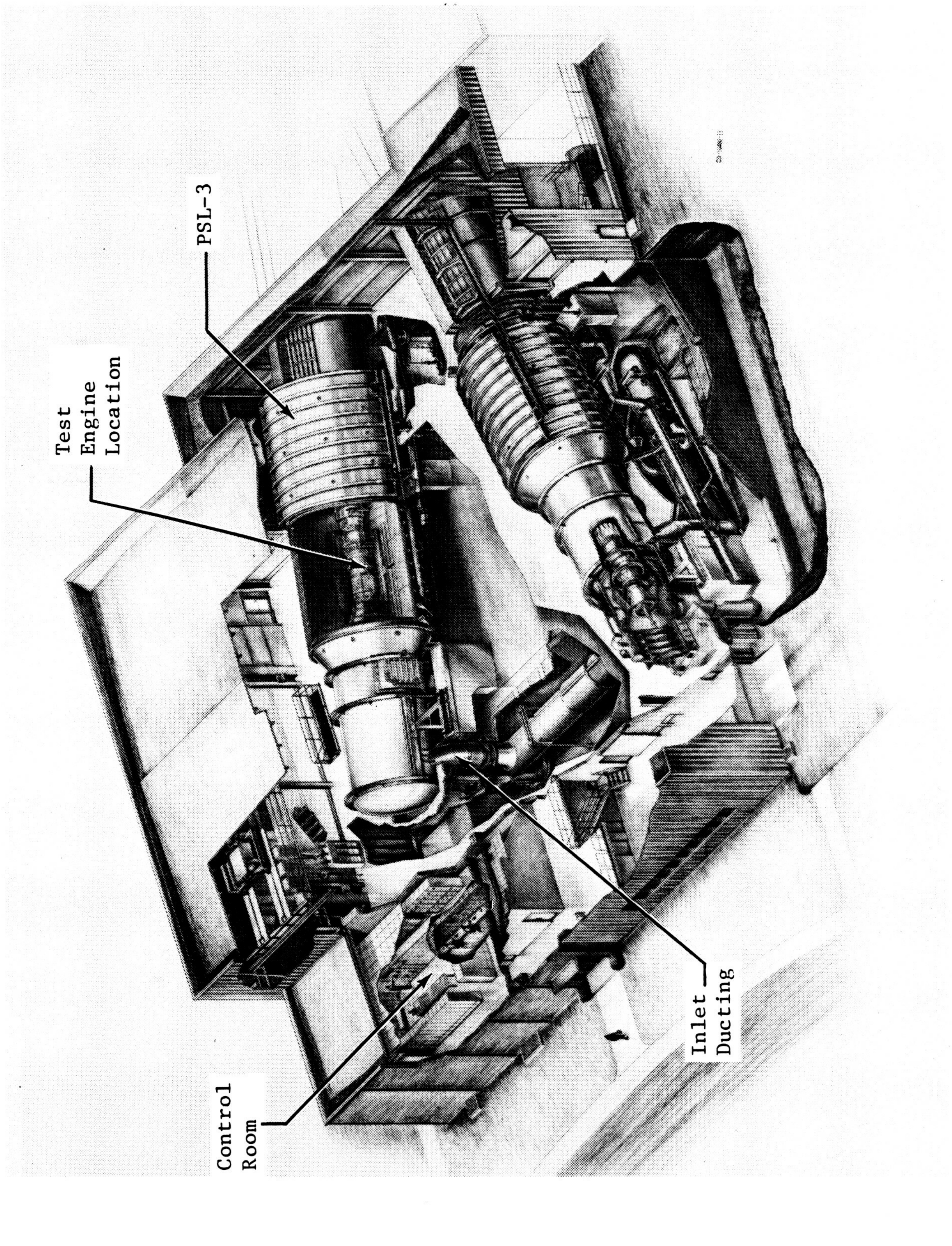


Figure 22. Engine Test Building.

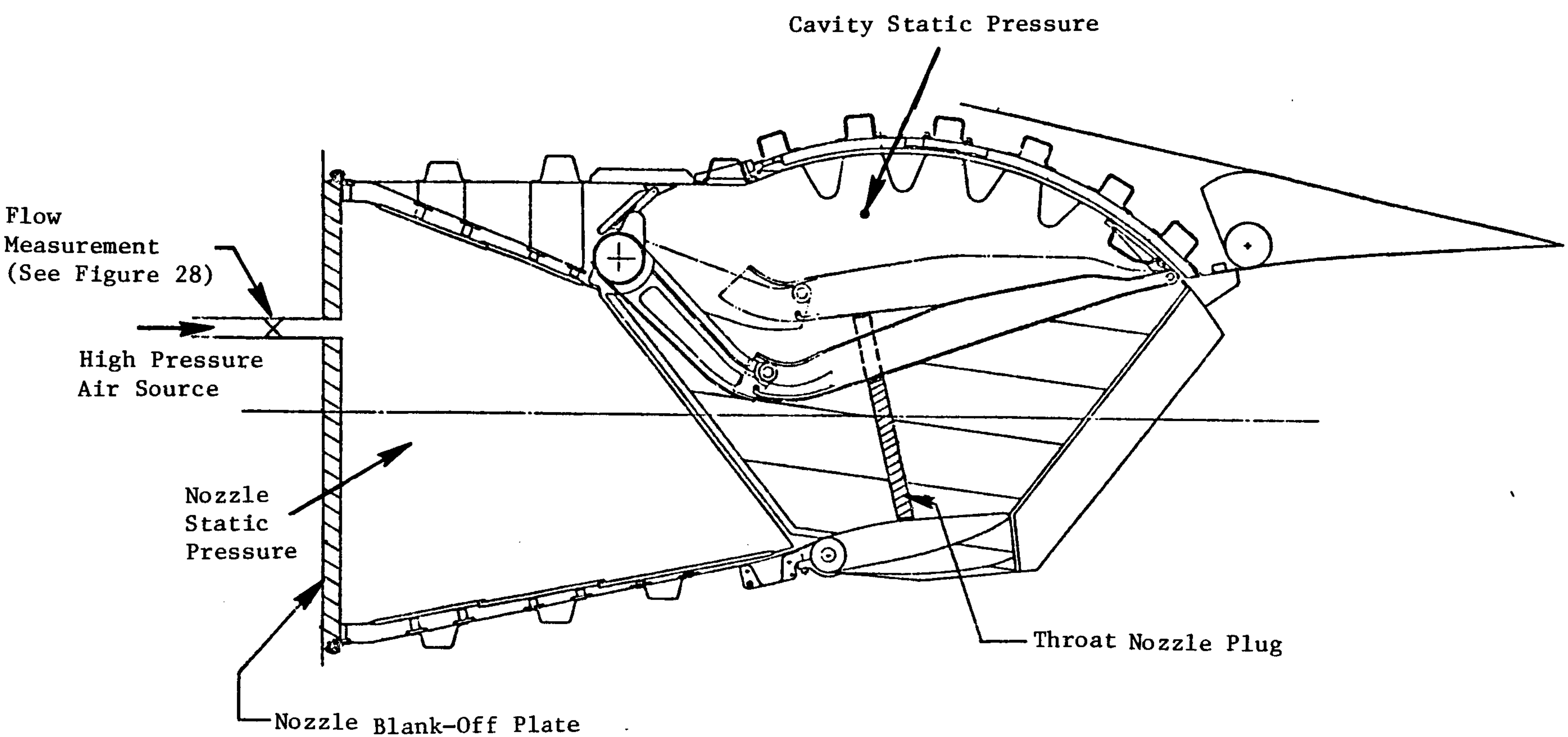
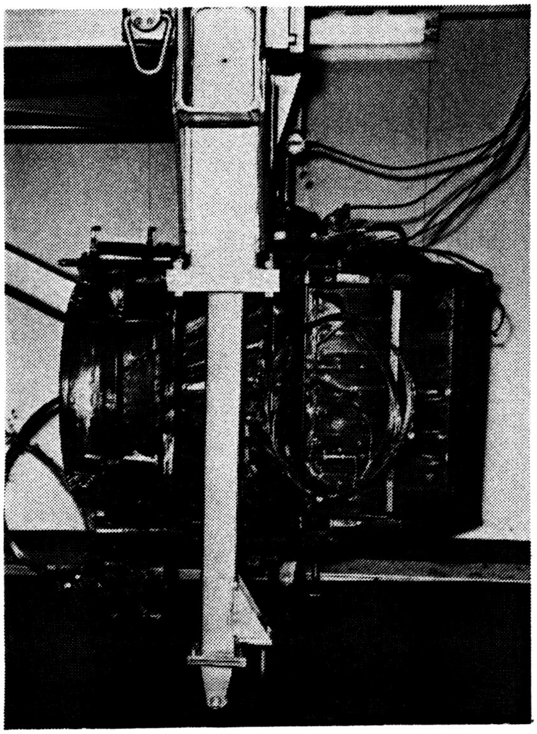
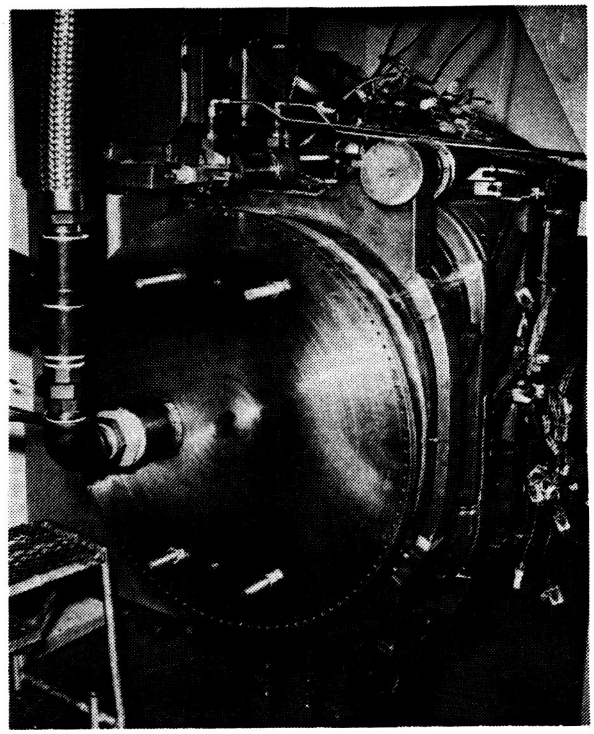


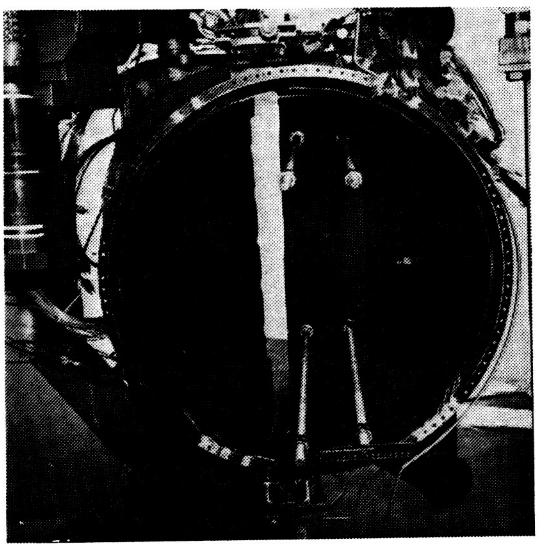
Figure 26. Cooling-Flow and Leakage Test Setup.



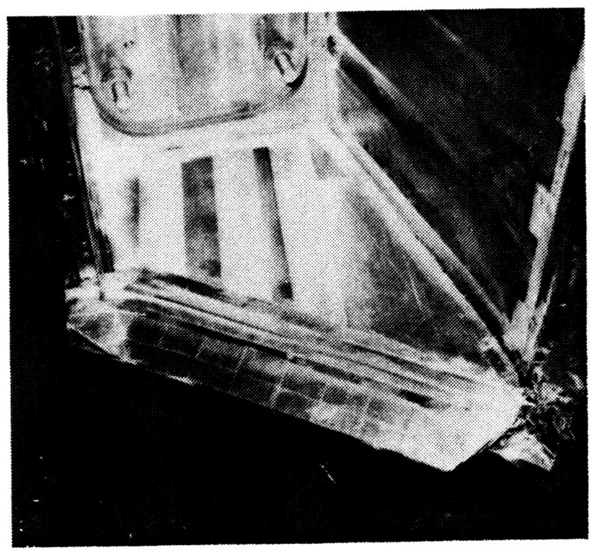
ADEN Mounted in Leakage-Test Facility



Blank-Off Plate



Typical Nozzle Plug



Taping of Leakage and Cooling Paths

Figure 27. Leakage-Test Setup.

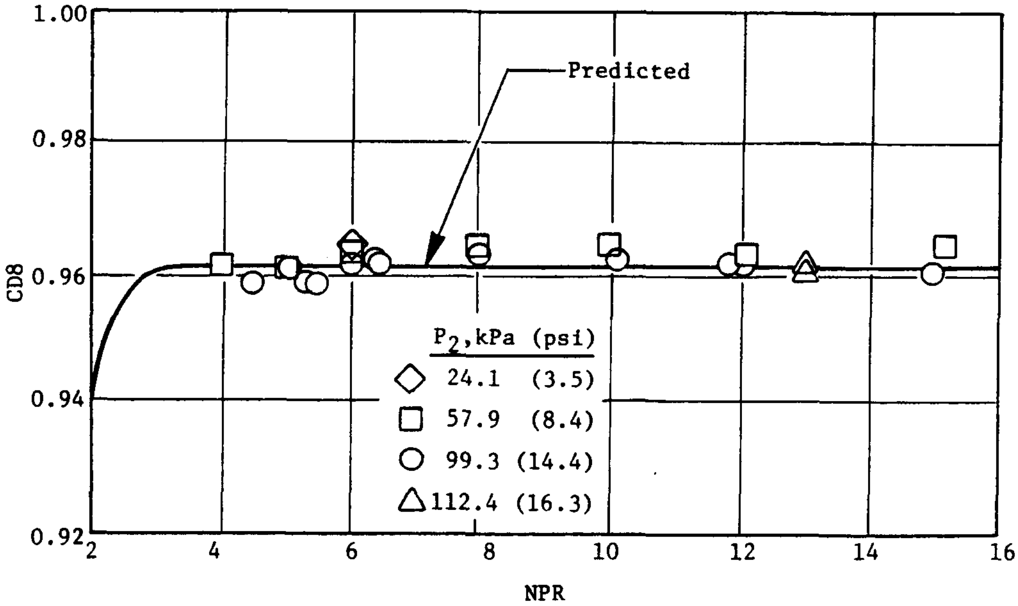


Figure 32. Measured Versus Predicted Nozzle Discharge Coefficient as a Function of Nozzle Pressure Ratio for the Conic Nozzle.

4.3 SUMMARY OF ADEN RESULTS

A summary of the F404/ADEN Altitude Test is presented in Table 2. Testing included 56 hours of engine running time. Of these 56 hours, over 14 hours were under reheat power conditions, and 6.5 hours of vectored operation were accomplished. No vibration, cooling, or actuation problems were encountered during the test. Visual inspection of the ADEN hardware revealed no distress as a result of this testing. Posttest photos of the hardware are shown in Figures 33 through 38.

Table 2. F404/ADEN Altitude Test Summary.

- 56 Hours Total Running Time
  - 14.25 Hours Augmented
  - 6.5 Hours Vectored
- No Vibration, Cooling, or Actuation Problems
- T_8 up to 1937 K (3488° R)
- NPR up to 18
- P_2 from 24.1 to 124.1 kPa (3.5 to 18.0 psi)
- Nozzle ΔP up to 331 kPa (48 psi)
- VEER Vectoring from -15° to +15°
- Flight-Weight Hardware

Figure 33. Augmentor (Posttest).

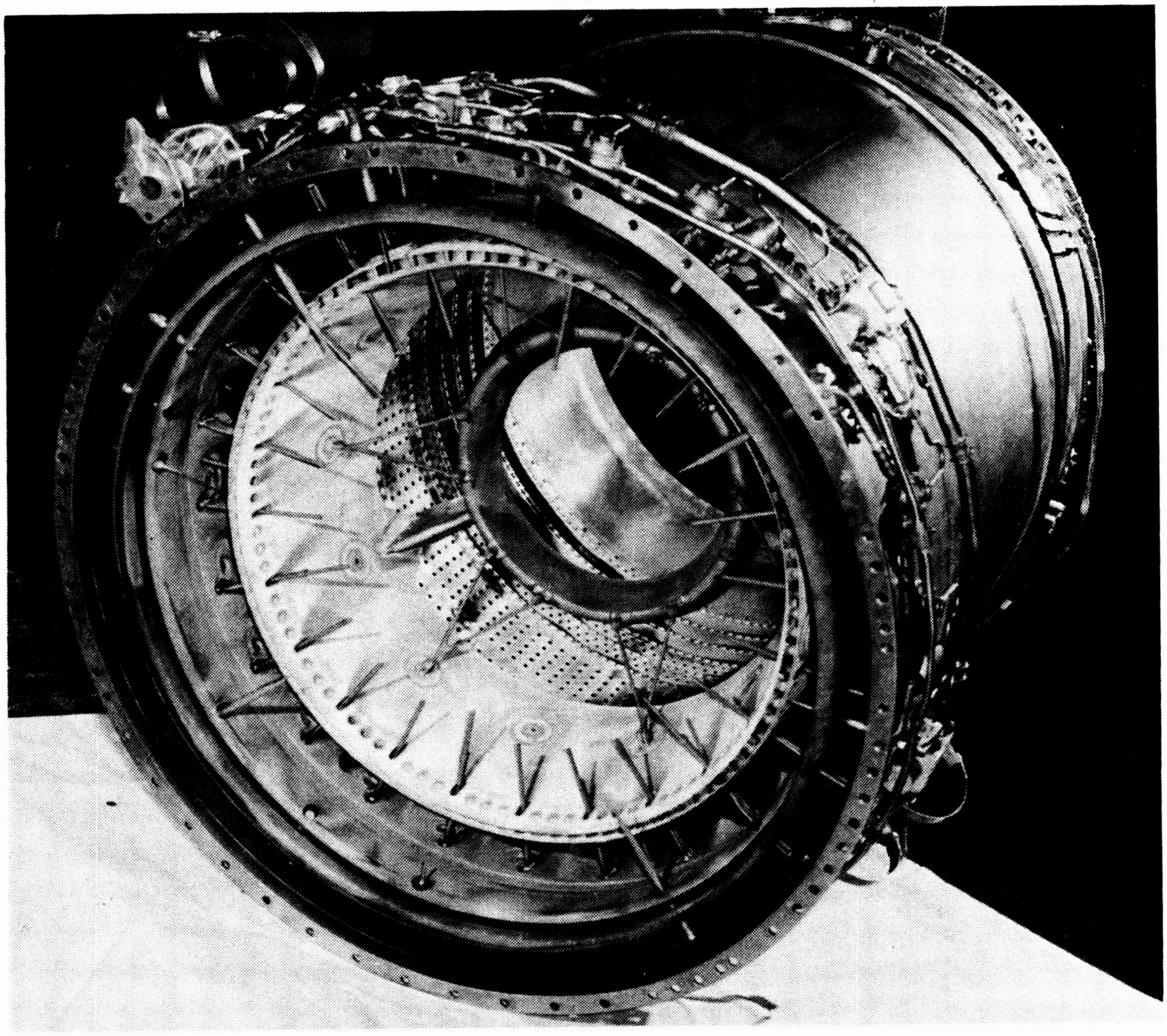


Figure 34. Augmentor (Posttest), Forward Looking Aft.

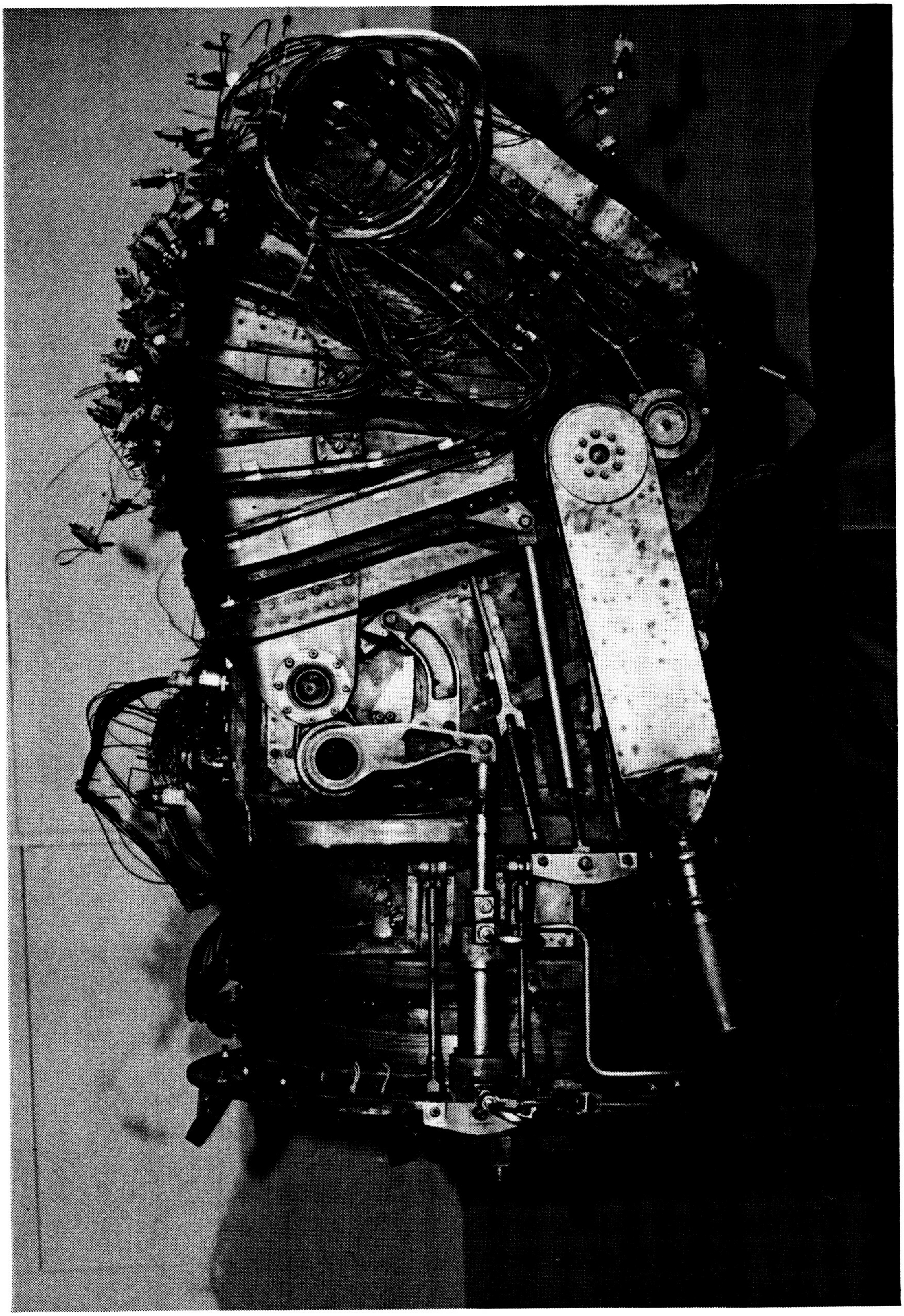


Figure 35. ADEN (Posttest).

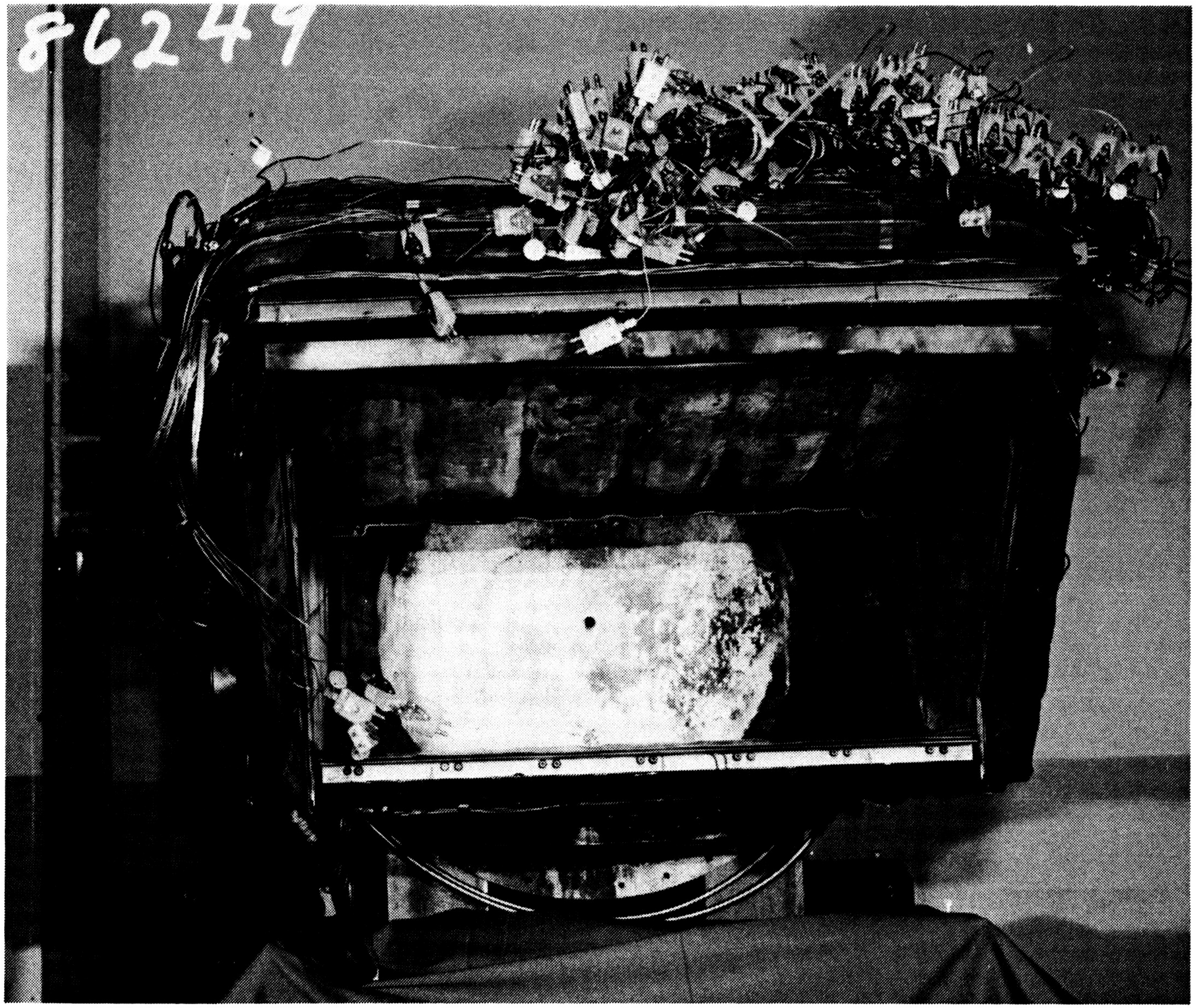


Figure 36. ADEN (Posttest), Aft Looking Forward.

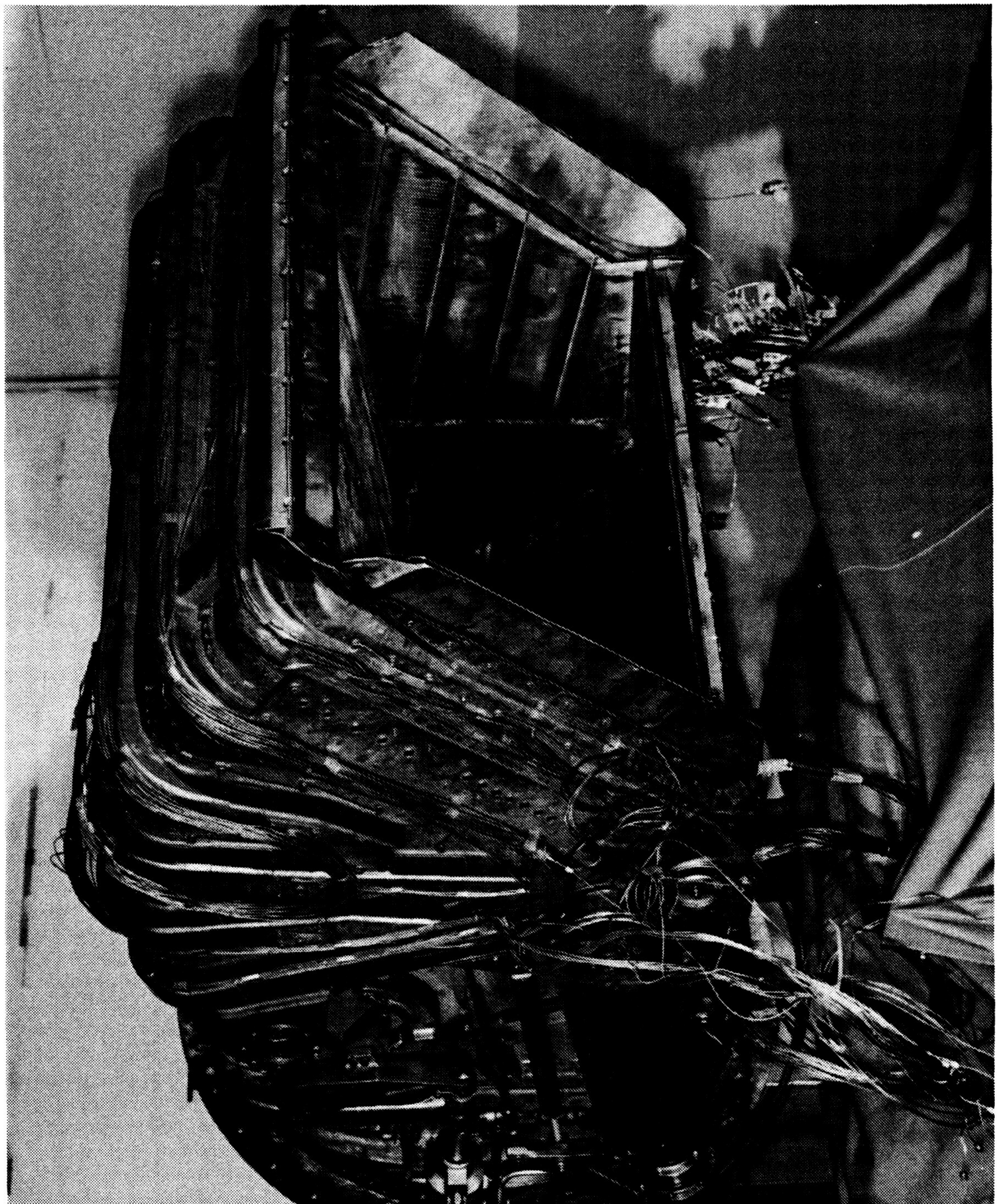


Figure 37. ADEN (Posttest), Oblique View.

Figure 38. ADEN Liners (Posttest).

The test covered a wide range of conditions. Nozzle-throat temperatures (T_8) up to 1937 K (3488° R) at reheat along with nozzle pressure ratios up to 18 were tested. The inlet pressure varied from 24.1 kPa (3.5 psi) to 124.1 kPa (18 psi). The nozzle maximum pressure loading was 331 kPa (48 psi) at maximum dry power and 312.2 kPa (46 psi) at reheat conditions.

Vectoring using the VEER was demonstrated for VEER angles from -15° to +15° relative to the nominal unvectored VEER position. Vectoring had no measurable effect on engine operation, and no vibration, cooling, or actuation problems were encountered during the vectoring portion of the test. Vectoring was accomplished during both dry and reheat conditions.

Fan-shaft stress levels were compared between the conic nozzle and ADEN. There was no measurable difference in the fan-shaft stresses between the two nozzles, indicating that the ADEN does not produce additional stresses in the fan shaft.

Table 3 summarizes all testing to date on the ADEN. The ADEN has been run for a combined total of 151 hours on the YJ101 and F404 engines. Vectoring has been successfully demonstrated using both the VEER and the deflector bonnet. Throughout this testing no nozzle vibration, cooling, or actuation problems have been encountered with the ADEN.

Table 3. Summary of All ADEN Testing.

- 151 Hours Total Running Time
  - 28 Hours Augmented
  - 8 Hours Vectored (3 Dry, 5 A/B)
- No Vibration, Cooling, or Actuation Problems
- VTOL Mode Deflector Angles from 0° to 98° on Max A/B
  - T_8 Up to 1967 K (3540° R)
- NPR up to 18
- Maximum Structural ΔP: 331 kPa (48 psi)
- VEER Vectoring from -15° to +15°
- Met Expected Performance

4.4 NOZZLE PERFORMANCE

Nozzle performance is reported for the nonafterburning test points including both the unvectored and the vectored VEER positions. Only a limited amount of nozzle performance data is reported for the afterburning conditions, however, because nearly all the A_8 data were taken at afterburner equivalence ratios (EQVAB) below 0.6. This equivalence ratio is defined as: $EQVAB = WFAB/WFAB_{stoichiometric}$, where WFAB is the afterburner fuel flow and